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WIND POWER PROJECTS OF THE FRENCH ELECTRICAL AUTHORITY

R. Bonnefille

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16. Abstract

Systematic measurement of the wind power distribution in France has shown that the design of wind generators involves two basic problems: the irregularity of the energy supply and the mechanical strength of the assembly. Since these problems have largely been solved for generators of less than 10 kW, the main body of this discussion deals with practical tests on one average-power and two high-power generators. Other variants tested in France and other countries are described in less detail. Furthermdevelopment of average-power generators with an output on the order of 100 kW is recommended.

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Foreword

The mention of wind power in 1974 immediately elicits a strong positive response from environmentalists and anyone interested in clean energy sources. As this year begins, the current energy crisis appears to all concerned as an opportunity to return to the possibility of using wind power.

It must be acknowledged, of course, that wind power is one of the oldest domesticated natural power sources in mechanical form, used primarily to propel ships and drive mill- and pump-wheels. These are two well-developed modes of use. The large sailing vessels have been replaced with steamships, ships driven by explosion engines, and finally nuclear vessels. At the same time, the art of sailing is becoming more refined every day. Old-fashioned windmills have disappeared, but windmill-driven pumps continue to operate.

During the energy crisis following the Second World War, there were some attempts to build high-power wind generators to produce electricity. All of these attempts cannot be termed failures, but they were all halted when the cost of petroleum products went down. Efforts to develop and perfect these assemblies continued on only a few small versions used in isolated areas, where they have been found economically feasible, but these small assemblies are about to give rise to a new generation of wind generators.

The following discussion will focus on the uses of wind power without going into detail on foreign projects, which of course must be kept in mind, but expanding on the contributions made by the French Electrical Authority, especially from 1947 to 1966.

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WIND POWER PROJECTS OF THE FRENCH ELECTRICAL AUTHORITY

R. Bonnefille,
Department of Atmospheric Exchange and Pollution, Research and Testing Division, French Electrical Authority

1. Wind and Wind Power /5*

A few basic concepts on wind are necessary to an understanding of wind power. Extensive efforts to understand the nature of wind as it occurs from 0 to 100 m above the ground have been made during the last two decades, 1947 to 1966. In France these efforts may primarily be attributed to the French Electrical Authority at the instigation of its Director of Research and Testing at the time, Pierre Ailleret [102, 105, 112, 115, and 116].

1.1. Measurement of Wind Power

In 1946, an integrating anemometer was developed by the Montrouge Meter Company; 350 of these devices were mass produced and installed in France and overseas. The results have been carefully analyzed. This assembly required a parameter proportional to the wind power capable of being collected by an airscrew; considerations of fluid mechanics based on highly simplified assumptions (cf. Section 1.2) show that the cube of the speed V of the wind may be this universal parameter.

Using this principle, maps were prepared showing the wind energy available per year expressed in kWh/m^2 of area swept by the wind generator (Fig. 1). For example, in a few areas on the northwest coast of Brittany, 5000 kWh/m^2 are available; an airscrew 30 m in diameter stirring a circular area of 700 m^2 would

* Numbers in the margin indicate pagination in the foreign text.

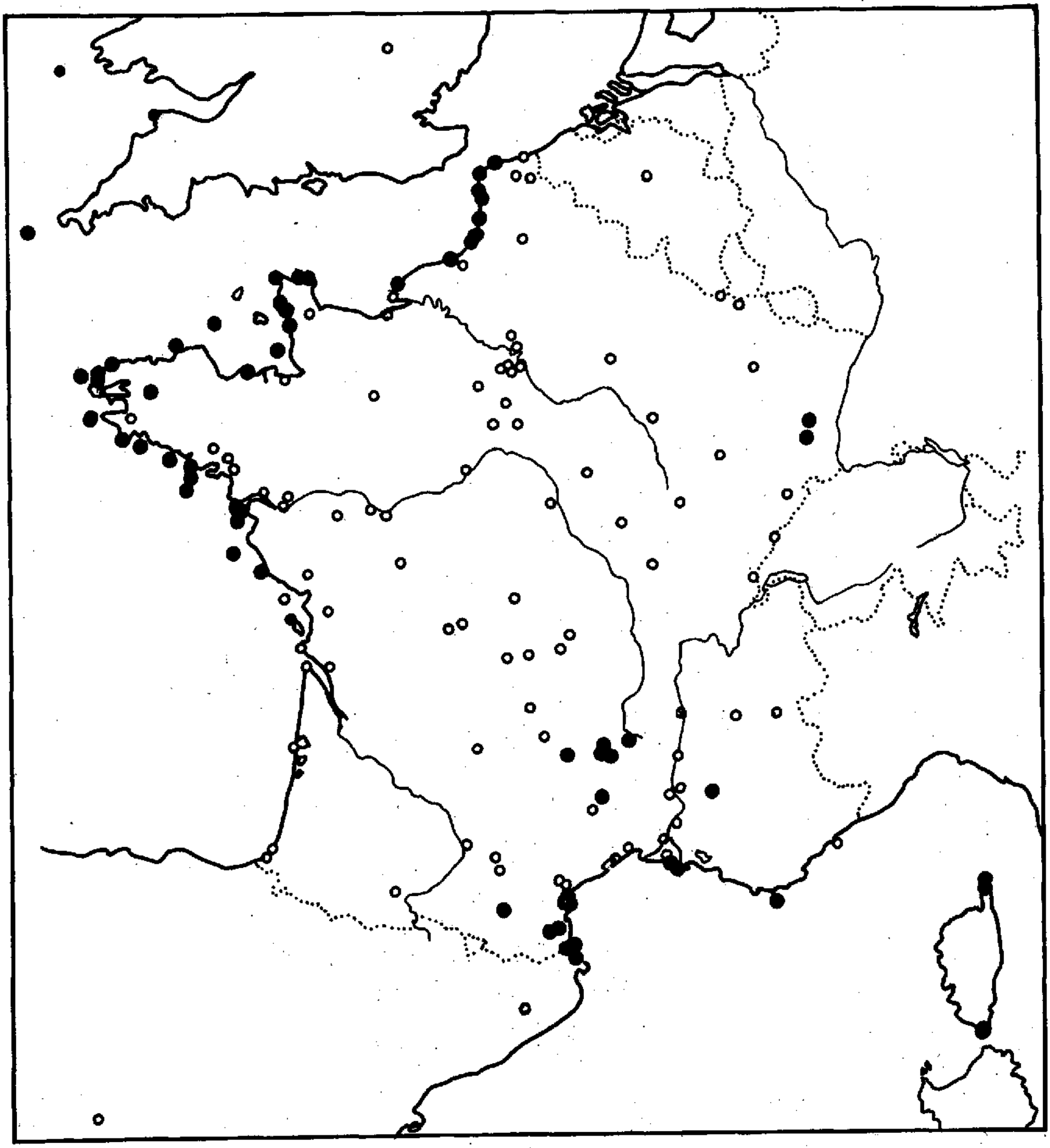


Fig. 1. Yearly distribution of wind power at 40 m above the ground. ● More than 3000 kWh/m^2; o Less than 3000 kWh/m^2.

theoretically be able to collect 3.5 GWh per year! Actually, this figure must be divided by a factor of 2 to 3 to obtain a value closer to the real order of magnitude. Thus it may be assumed that 1000 wind generators of this type distributed along the coast would deliver more than 1 TWh per year [104, 105, 111, 113].

At this point in development, any extrapolation from these figures is questionable and may lead to a premature rejection of wind energy, since the "CdC-Ailleret" anemometer, the basis for the use of wind power in France, is not a convincing argument in itself for the real possibility of controlling this type of energy; it was first necessary to try a practical test. It is this test which we will attempt to describe objectively, 10 years after its conclusion, in order to point out:

-- on the positive side, the aerodynamic efficiency of the assembly, that is, the proportion of the theoretically available wind power which it actually captures;

-- on the negative side, the technical problems raised by large wind generators.

Nevertheless, the anemometer developed by the French Electrical Authority and the French Department of Lighthouses and Beacons has furnished attractive results [112, 115, 116]:

-- Wind power is localized primarily close to the coast in the temperate zone; it is not related to hydraulic energy. It /6 is stronger in the winter than in the summer, slightly stronger at a low distance from the ground, and stronger in the daytime than at night. The power is fairly uniform from year to year (there are no extremely windy or extremely calm years) and even from trimester to trimester. It is regular on a 1-hour scale, but extremely irregular on a minute or semi-weekly scale. The conclusion is that the Atlantic coast of Europe has a good yearly supply of average wind power, but this power is randomly distributed; however, there are satisfactory mathematical models for this distribution [210].

-- In addition, the spatial distribution of wind is extremely irregular; neighboring sites may differ widely as to the amount of wind power available. The wind generator itself produces considerable disturbance; its long wake (several kilometers) is a relatively devalorizing factor for sites. In conclusion, the choice of wind power sites is a difficult problem, since the blades of airscrew machines are subjected to extremely irregular mechanical stresses.

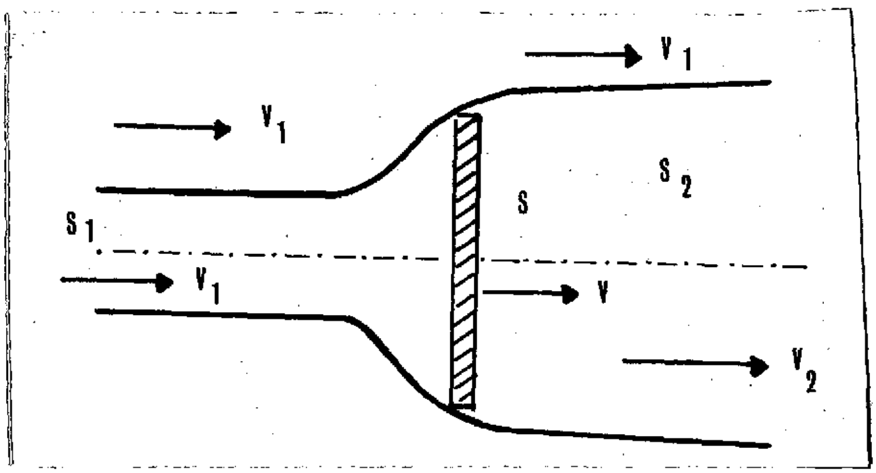
These two groups of results relative to wind bring out the two largest problems with regard to wind generators: the irregularity of the energy supply and the mechanical strength of the wind generator. These problems have already been solved for small assemblies (less than 10 kW); a solution for average-power generators (100 kW) is within sight, but so far the solution for high-power generators has only been sketched in [114, 117, 205, 207].

1.2. The Betz Formula [100]

The proportionality of wind power to the cube of the wind speed mentioned above constitutes the Betz formula, familiar to wind power specialists. Since in the following discussion we will refer solely to the efficiency of wind generators, the ratio between the power they generate and the total aerodynamic power which they could extract from the wind, that is, the "Betz" power, it is necessary to state the basic assumptions of this formula.

It is assumed that the wind motor is placed in an unlimited fluid moving uniformly upstream and downstream from the motor, to infinity. It slows a small fraction of the fluid, and this kinetic energy deficit is transformed into mechanical energy. Since the fluid which has performed this work must retain enough speed to travel away from the device, the generator must use only a limited fraction of the kinetic energy of the fluid involved.

Let us diagram the wind generator schematically by the disk of area S which it sweeps, intersected perpendicularly by the wind speed V, that is, by an air mass of revolution with cross section S_1 and S_2 and average speeds V_1 and V_2 far upstream and downstream from the disk, and a weight per unit volume ρ.



The continuity and the noncompressibility of the fluid are given by the relationships: /7

$$S_1V_1 = SV = S_2V_2$$

Let us express the loss of power of the fluid upon passing through the disk in two ways. First, the kinetic energy loss is:

$$\boxed{W_1 = \rho\frac{SV}{2}(V_1^2 - V_2^2)}$$

Second, the variation in momentum as the fluid passes through the disk represents a stress exerted on the disk by the fluid:

$$\boxed{F = \rho SV(V_1 - V_2)}$$

whose corresponding power is:

$$\boxed{W_2 = FV = \rho SV^2(V_1 - V_2)}$$

The equality of the two power values results in the simple equation:

$$V = \frac{V_1 + V_2}{2}$$

Let us assume $V_2 = aV_1$; let us express the power as a function of parameter a which is unknown a priori, but will necessarily range from zero to one:

$$\boxed{W = \frac{1}{4} \rho S V_1^3 (1+a)(1-a^2)}$$

The function W(a) will reach a maximum for a = 1/3:

$$\boxed{W_{max} = \frac{16}{27} \left(\frac{1}{2} \rho S V_1^3 \right)}$$

This is the Betz formula, giving the maximum energy available across an area S downwind from a wind of speed V_1. With $\rho = 1.25\ kg/m^3$, a satisfactory average, this becomes:

$$\boxed{W(kW/m^2) = 0,37 \left[\frac{V(m/s)}{10} \right]^3}$$

an equation which serves to estimate the wind power theoretically available on the basis of measurements of the wind speed at a point on the site where this is significant.

2. Actual Wind Generators /9

This section provides a review of installations which have actually been operated, presented in the form of a synthesis of data on these generators contained in the literature. The purpose is more informative than interpretive.

The table on the next page is a collection and summary of the basic data on a few machines whose operating characteristics may indicate the possibilities of wind power.

This table includes some information on the largest wind generator built so far: the Morgan-Smith-Putnam generator (1250 kW) installed in the US in 1941, one of whose blades broke on March 26, 1945. The project was subsequently abandoned due to high operating costs ($1.25 million). Nevertheless the machine did operate for 1030 hours, from October 1941 to May 1945, delivering 360,000 kWh; its output reached 1500 kW under a 30 m/sec wind. The table also includes one of the oldest machines, with an output of 100 kW, built in Crimea in 1931 and tested there over a period of 2 years. In the USSR, 18 m, 28 kW machines have also been operated, especially in connection with the Telechev tractor and machinery plant and the Mikolskoye plant [106, 201].

2.1. Wind Generators Built by the French Electrical Authority

The French Electrical Authority has tested three high-power machines. These projects were based on research from 1948 to 1966 by the Wind Power Division under the direction of M. Argand, within the Research and Testing Division, in cooperation with French designers and research organizations: the Scientific and Technical Research Agency (BEST), NEYRPIC and its subsidiary SOGREAH, etc.

2.1.1. The Nogent-le-Roi 800 kW Wind Generator

This machine (Figs. 2 and 3) was equipped with a three-blade[1] light alloy plate airscrew with fixed setting; the blades were embedded in the hub.

[1] This is the optimum number so that the airscrew will not rotate too slowly while at the same time retaining an inertial ellipsoid of revolution.

CHARACTERISTICS OF A FEW AVERAGE- OR LARGE-POWER WIND GENERATORS HAVING BEEN IN OPERATION

SITE	Designer (foreman)	Diameter and direction of operation, m[1]	Rated output (kW)	Rated wind speed (m/s)	Types of blades	Example of output
ALGERIA						
Grand-Vent	Andreau-Enfield (BEA - EGA)	24.4 AV	100	13	Variable setting, articulated	180 h
GERMANY						
Stötten	Studiengesellshaft Windkraft	34 AM	100	8	Variable setting, plastic	
ANTILLES						
La Barbade	Brace (Québec)	9,75AM		10		Irrigation, 4 ha
DENMARK						
Bogo	Lykegaard Smith (SEAS)	13	45	5		80 MWh/year (typ.)
Vester-Egesborg	- -	8,2	13			25 MWh/year (typ.)
Gedser	- -	24,4	200	6		200 MWh/year (typ.)
GREAT BRITAIN						
Costa-Head (Orkney Islands)	John Brown C°	15,2 AV	100	15,6	Wood	With 400 kW electrical generating unit 400 kW
Crandfield (Bedfordshire)	Dowsett Holdings (U.K.Ministry)	12	25	11		85 MWh/
Ile de Man			100			
FRANCE						
St.Rémy-des-Landes (Manche)	Neyrpic (EDF)	21,2 AV	132	12,5	Plastic with variable setting	52 MWh/month (December 1965)
- idem -	- idem -	35 AV	1 000	17	- idem -	200 MWh/month (November 1963)
Nogent-le-Roi (Eure et Loir)	BEST-ROMANI (EDF)	30,2 AV	800	16,7	Metal with fixed setting	
Sept-Iles	Aérowatt	9.2 AM	4,1	7	Aluminum with variable setting	200 kWh/year (1973)
Le Bourget	CEM (Darrieus)	20 AV	12	6	Fixed sheet-metal	
USSR						
Balaklava	Tz A.G.I.	30 AM	100	10,5	Light metal	200 MWh/year (1933)
U.S.A.						
Granpa's Knob (Vermont)	Morgan-Smith C° (Putman)	53 AV	1 250	7,5	Stainless steel	360 MWh

[1] AV indicates that the airscrew is downstream from the motor, and AM that it is situated upstream in relation to the wind.

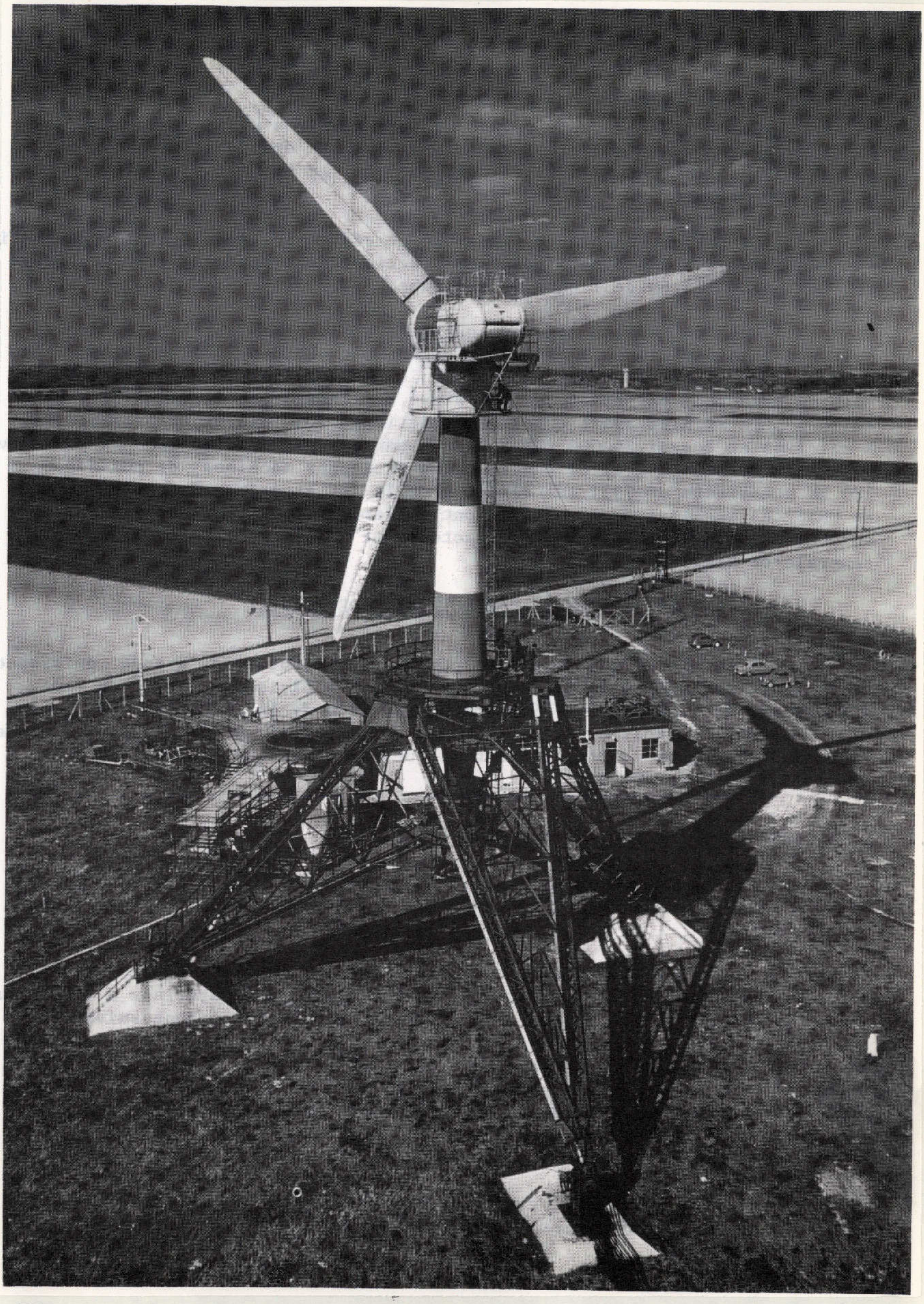


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Fig. 2. The BEST-Romani wind generator at Nogent-le-Roi (Eure and Loire). 30.2 m; 800 kW.

The blades, tested in wind tunnels (Eiffel, Chalais-Meudon, St-Cyr-l'Ecole and Poitiers) and, from the standpoint of strength of materials, by the Toulouse Aeronautics Association, met the following specifications:

-- the airscrew is able to operate at a wind speed of 25 m/sec (90 km/h);

-- at rest the airscrew is able to tolerate a 250 km/hour wind;

-- the airscrew is able to tolerate 35 m/sec gusts (125 km/ /hour) without damage.

The speed of rotation of the airscrew was constant, since the machine was connected to the electrical network (50 Hz, 60 kV) through a synchronous alternating generator (800 kW; 3000 V) with a double transformation stage (3/15/60 kV) and a 15 kV line 12 km long. /11

The airscrew and the alternating generator were linked by two planetary step-up gears (Fig. 3) with ratios of approximately 7.5 and 3 and by a coupling allowing transmission of torque alone and not the deformation which must be expected due to the design of the hub and the mechanically welded heavy metal plate blades.

The other significant characteristics are as follows:

-- diameter of airscrew: 30.19 m;

-- rotation speed: airscrew 47.3 rpm; alternating generator 1000 rpm;

-- rated output: 800 kW with a 16.7 m/sec wind (60 km/hour);

-- height of shaft: 32 m above ground;

-- total weight (except substructure): 160 tons.

The value of the Nogent-le-Roi plant was that it virtually served as a test bench for 5 years (1958 to 1963). Thanks to a large number of reports prepared by BEST at the request of the EDF [Electricité de France; French Electrical Authority], it is possible to furnish a great many details on the operation of this machine. Two airscrews were tested in turn: the first, slow-speed airscrew, described above, held up very well; the only failures were of mechanical origin and did not bring the basic operating principles of the airscrew into question. On the other hand, one blade of the second, high-speed airscrew broke during testing.

2.1.1.1. Goals of Testing Program [301]

Before entering on the history of this machine, we might analyze the goals of the Nogent-le-Roi testing program:

-- to measure the performance of the generator in order to set up a basis for evaluating the energy production capacity of future machines; the purpose here was to surpass the results obtained at St-Cyr-l'Ecole on a small-scale model 40 m above the ground, by building a full-size assembly.

-- to analyze energy losses: in designing wind generators, cost reductions due to imperfections must be balanced against the attendant loss in efficiency; to balance these two factors, the distribution of energy losses must be known;

-- to determine the optimum excitation setting: previous experiments revealed the possibility of obtaining automatic

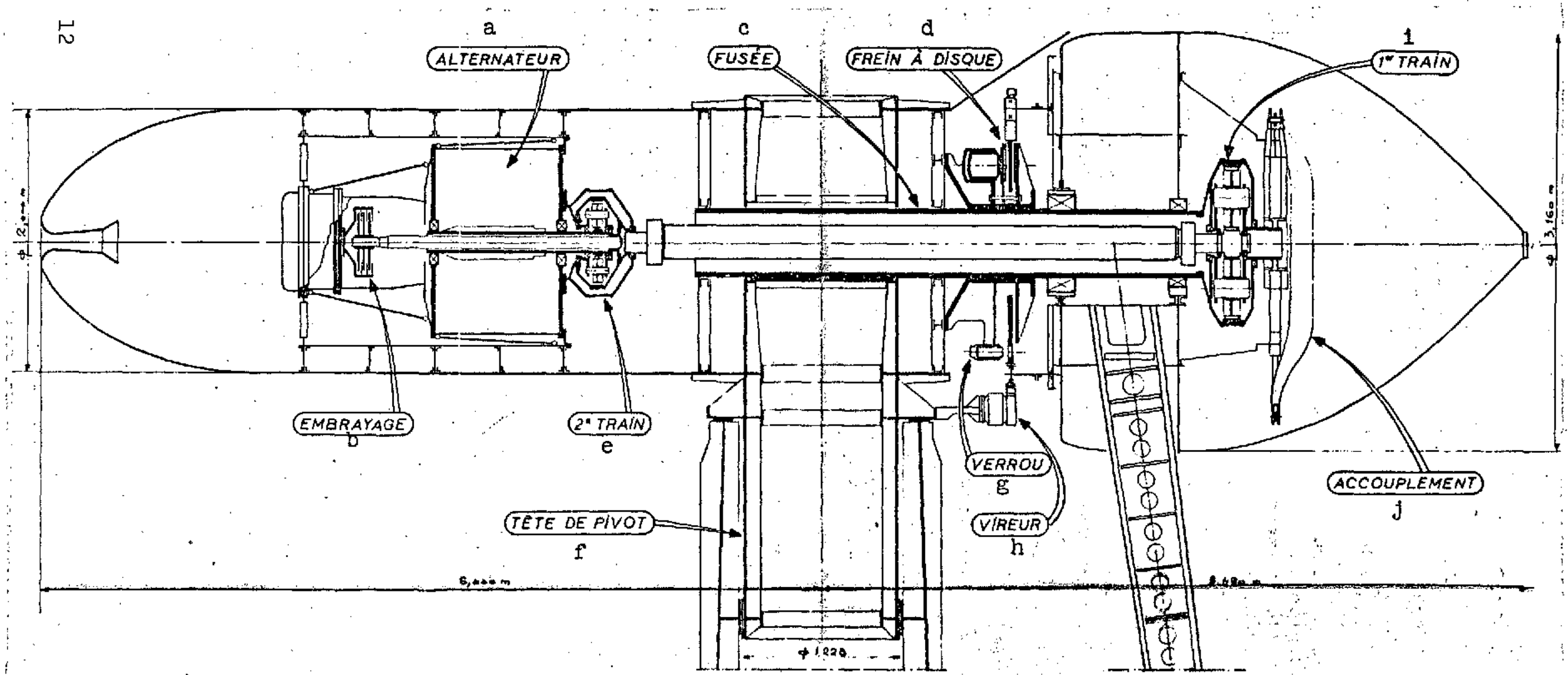

Fig. 3. Schematic cross section of the pod of the Nogent-le-Roi wind generator.

Key:
a. Alternating generator
b. Clutch
c. Engine nacelle
d. Disk brakes
e. First gear
f. Pivot head
g. Lock
h. Turning-gear
j. Coupling

setting with constant excitation of the generator, but whether or not this was the best method remained to be determined;

-- to develop methods of use: for example, procedures for connecting the machine or disconnecting it under low wind, etc;

-- to compare braking procedures: two systems (mechanical and /13 electrical) were tested simultaneously;[2]

-- to simplify servo relationships: the generator is equipped with the maximum equipment which can be provided (slaved and manual orientation, for example); however, one must still ask whether this equipment is excessive or whether an important phenomenon has been neglected;

-- to check strength of materials computations: this is a new technique in which standards have yet to be defined; thus the maximum stresses must be measured;

-- to see whether the overall tilt is really necessary;

-- to test the connection to the ground by flexible cables, allowing leeway for several coils of the cable within the pivot to preclude the necessity for a rotating collecter;

---

[2] If the setting of the airscrew blades of a wind generator is fixed, adjustment may be obtained automatically and with no expenditure of energy, as Darrieus proposed in 1927, merely by the fact that the mechanically powered generator is connected synchronously, or even merely quasi-synchronously, to a large network. This is because the incident wind is the geometrical sum of a relative component derived from the rotation speed and the natural wind. When the latter speeds up, at constant rotation speed, the velocity triangle becomes distorted and part of the blades undergo a "speed loss"; the power from the airscrew reaches a maximum, decreases and begins to increase slowly once again only with very high wind speeds. On the other hand, the airscrew overspeeds when the generator is disconnected from the network.

-- to study the wake: in order to estimate the minimum distance between assemblies.

This program also served to define the measuring devices -- wattmeters, anemometers, gauges, etc. -- given the possibilities at that time; there is no point in enumerating their characteristics today.

2.1.1.2. Brief History of the Nogent-le-Roi Wind Generator [302-309]

A chronological review of the tests performed on the Nogent-le-Roi wind generator would be of value here, since this will show the series of operations to be performed in a case of this type, synthesize the failures and functioning of the generator, and stipulate the time required for the various basic procedures.

From March 15 to June 13, 1958: preliminary tests with a wind speed V of less than 12 m/sec. These tests dealt with the following points:

-- checking the validity of the starting and connecting procedures and the electrical stability at a low charge: after malfunctions in the starter had been repaired, the system was connected to the network without incident on April 2 with the generator in normal position and on April 10 with the blades at a 90° angle to the wind. The following operations were performed after the airscrew was facing into the wind:

* the alternating generator was started in an asynchronous mode and then synchronized; /15

* the airscrew was released and the clutch was engaged when it had reached the synchronization speed and had begun to overspeed.

When the airscrew was not in the wind, or when the wind was slight (the following operation is not recommended in high winds):

* a synchronous startup driving the airscrew and subsequent synchronization;

* release of orientation of assembly.

The stability is perfect within the power range 55 kW (zero wind) to 300 kW (12 m/sec wind);

-- <u>control of equalizing forces</u>: tests involving unguided rotation up to the synchronization speed were performed;

-- <u>study of the single-disk mechanical braking device</u>: this was the part of the machine which seemed to be the most problematic at first; a number of readjustments were necessary, but it ultimately operated perfectly;

-- <u>checking of the electrical braking device</u>: the electrical braking system operated satisfactorily after the response time of a circuit breaker had been reduced to less than 0.4 sec. With a wind speed of less than 10 m/sec it reduced the speed to 1 rpm, a speed at which the airscrew could be locked while still in motion. The combined action of both brakes, even in high winds, stopped the assembly in less than 2 rotations of the airscrew;

-- <u>control of lubrication</u>: there were numerous problems and leaks;

-- <u>control of heating</u>: here there were no problems since the efficiency of the radiators increases with the wind speed;

-- <u>tests on vibration</u>: the oscillations of the pod, recorded by three accelerometers, were found to be insignificant, with the

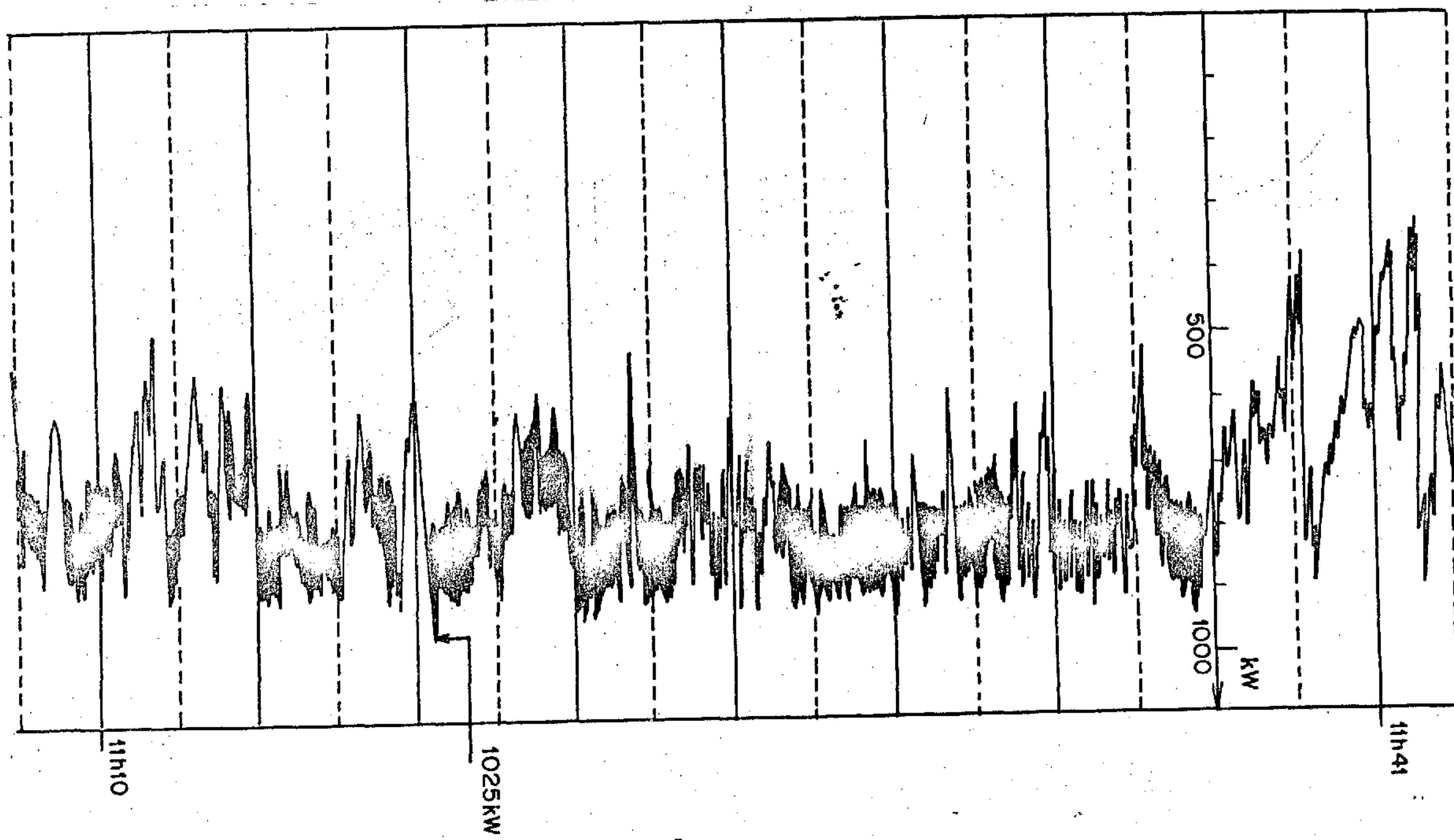

Fig. 4. Operation of Nogent-le-Roi wind generatr at maximum power, October 27, 1959.

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exception of those due to the blade's passing behind the pivot ($\pm 4'$), but these disappeared in high winds. High-speed cinematography of the blades showed there to be no vibration;

-- noise: the noise level was somewhat high, but no measures were taken; little attention was given to this problem since it did not seem to be very important;

-- study of orientation: the restoring torque was measured by means of a brake-dynamometer as a function of the drift angle; it was found to be much higher than that predicted from wind tunnel tests. The movement at the beginning of rotation was found to be aperiodic; with clearance of 45° or more, the assembly became oriented without vibrations or oscillations in a few seconds.

From June 19, 1958 to September 1958: further operation of equipment.

From September 1958 to April 16, 1959: new series of tests up to V = 17 m/sec including 122 hookups to the network and 171 hours of connected operation. The rated output of 800 kW was reached with a wind speed of 16.7 m/sec. Here the important points were as follows:

-- airscrew: this operated correctly, although the outside paint was in poor condition;

-- brakes: the mechanical brakes were used 200 times (delaying moment $4 \cdot 10^6$ mN). The electrical brakes operated correctly, reducing the speed to 0.2 rpm with a wind speed of 10 m/sec; /17

-- clutch: adjustments were necessary to preclude chattering and slipping above 700 kW;

-- stability of connection with network: this point was thoroughly tested, particularly the oscillation of the system, since the alternating generator was capable of non-damped pendular oscillation (3 Hz) which could result in stall.[3] Actually, the alternating generator-airscrew system oscillated at approximately 2 Hz, entraining perturbations with a maximum amplitude on the order of 40 kW; however, these were oscillations due to the blades' passing behind the pivot (2.35 Hz), an unavoidable phenomenon but an acceptable one, since this was not stall;

-- orientation: the spontaneous orientation system operated satisfactorily (2.8°/sec) with a wind speed of up to 17 m/sec);

-- heating: the maximum was 45° in the second step-up gear.

From April 17 to May 15, 1959: completion of assembly (particularly, installation of orienting unit).

From May 16 to October 4, 1959: there was little wind during the summer of 1959, and this period was used for development of the "on-board" measuring equipment.

October 5 to November 18, 1959: continuous operation with brief interruptions due to:

-- slipping of the clutch (October 18 and November 13);

---

[3] The extreme inconstancy of wind as a power source makes it necessary to equip the alternating generator with squirrel-cage shock absorbers to prevent any tendency toward oscillations. In addition, the connection to the networks must be made through an electrical line whose reactance should be low so that the synchronizing torque will be high enough, and whose dc resistance should be low so that negative damping does not develop.

-- problems in the oil circuits for the brakes and clutch (October 21 and 27);

-- extra time for assembly of the orienting unit (November 4);

-- mechanical damage to the shaft (November 18).

During this period the machine operated 931 hours, 195 of which were consecutive; it was connected up 164 times. The maximum output observed was 930 kW with a wind speed of 20 m/sec, with a peak at 1025 kW (Fig. 4).

The information drawn from this series of tests was as follows: /19

-- airscrew: this operated correctly (up to V = 24 m/sec);

-- brakes: as a safety measure, the mechanical brake was set up to operate a few seconds after the electrical brake, except in high winds;

-- step-up gears: due to the lubrication problems, constant levels were maintained in each gearbox, by means of a hand pump where necessary;

-- stability: the machine continued in steady-state operation without stalls or vibration even above 800 kW;

-- accident of November 18, 1959: the downstream bearing of the alternating generator was destroyed, resulting in damage to the shaft, the upstream bearing, and the fan of the alternating generator. The cause of the accident was not entirely clear. Apparently the capacity of the oil baths was too low or the bearings were pressed too tightly against the assembly. The conclusion was that

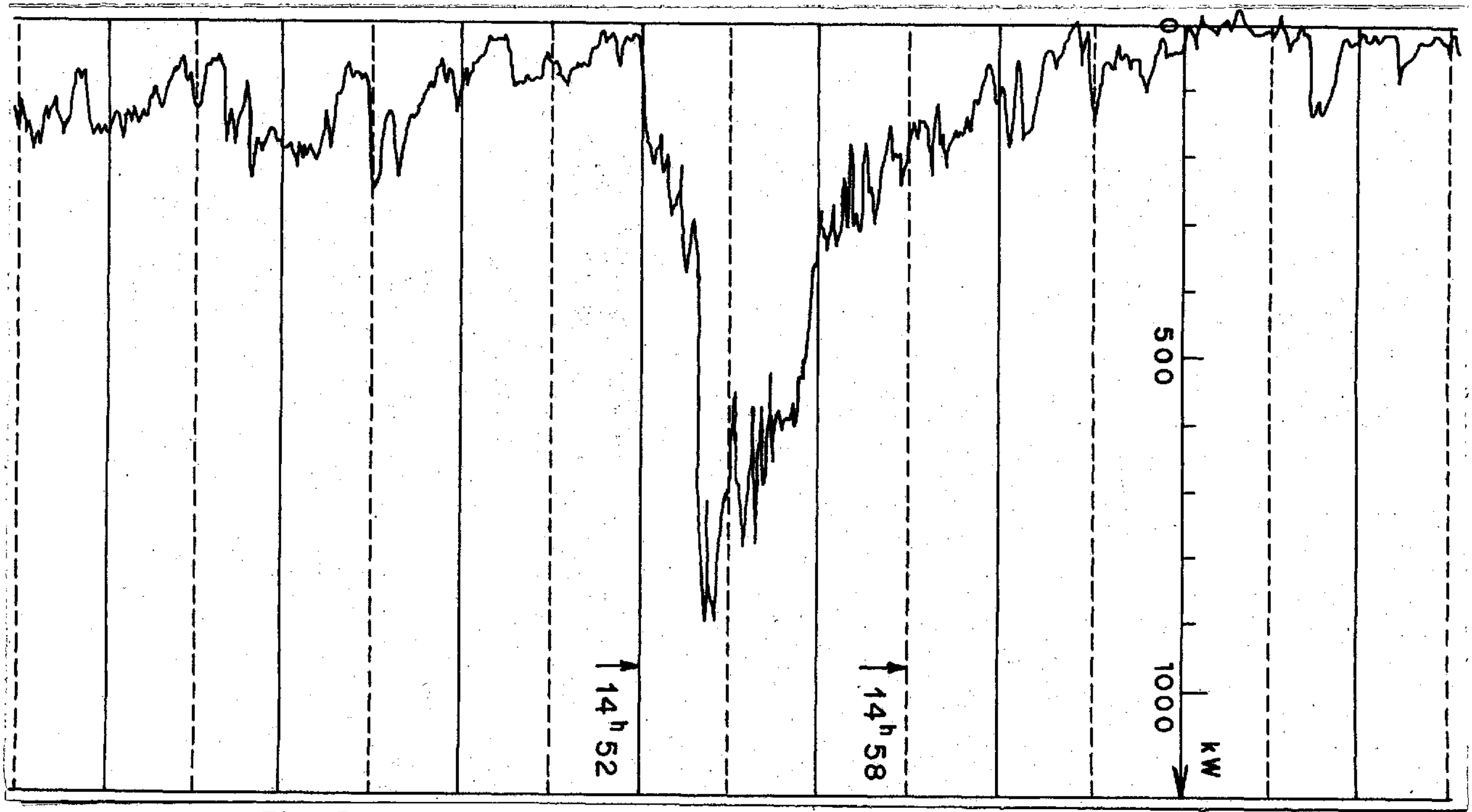

Fig. 5. Output variations of the Nogent-le-Roi wind generator during a strong gust on October 30, 1960.

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that lubrication of machines with step-up gears is a source of problems.

From November 18 to April 13, 1960: repair.

From April 13, 1960 to April 12, 1962: after the alternating generator had been reassembled, the machine was reconnected to the network on April 13, 1960. A number of problems ensued:

-- oil leakage from the first step-up gear;

-- problems with the hydraulic braking circuit;

-- problems with the electrical brakes;

-- heating of the second step-up gear, resulting in the disabling of some bearings (September 16, 1960);

-- play in the coupling (stoppage from July 4 to September 6, 1961);

-- cracking of the blade roots due to elongation of the rivets securing the blades.

Nevertheless the machine did reach an output of 1025 kW, minus 10 kW for excitation of the alternating generator (Fig. 4). It held up quite well under gusts; on August 30, 1960, the output increased from 300 to 900 kW in a few seconds (Fig. 5). The mean outputs tolerated were as follows:

800 kW	for	1 hour
825 kW	for	4 consecutive hours
683 kW	for	12 consecutive hours

The generator satisfactorily tolerated a storm on January 11, 1962, during which the wind reached a speed of 30 m/sec.

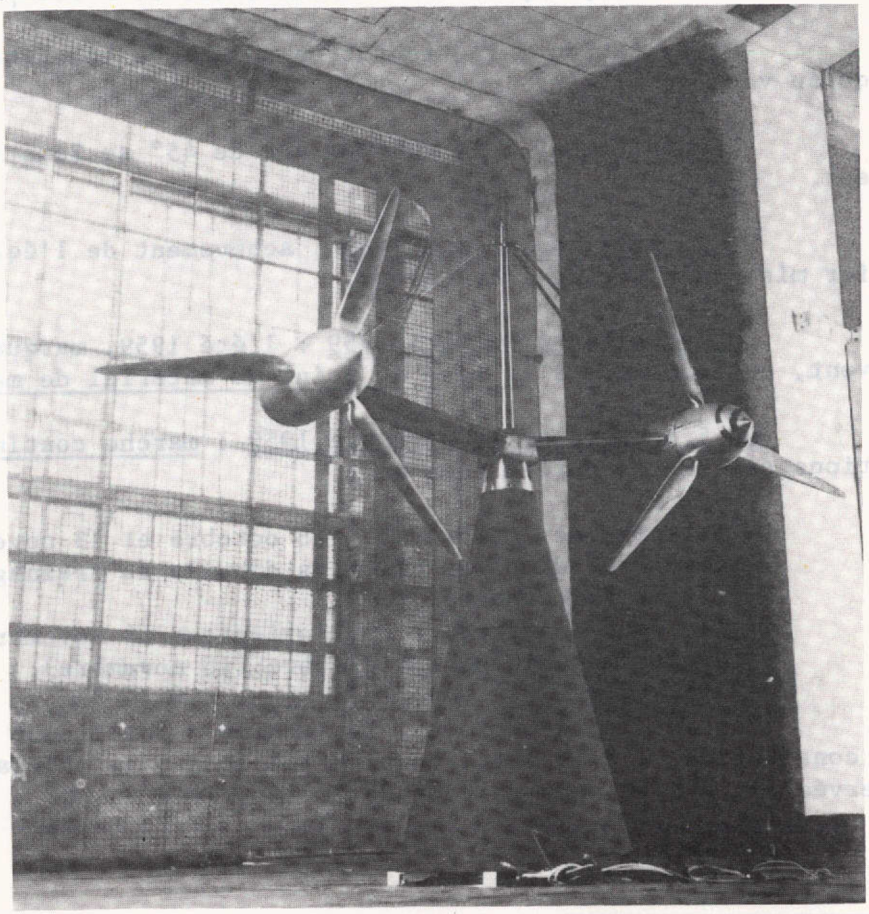

Fig. 6. Model of assembly of two 2 MW machines equipped with 45 m airscrews in the course of wind tunnel testing (Bréguet at Villacoublay).

2.1.1.3. Conclusions on the Operation of the 800 kW Nogent-le-Roi Wind Generator /21

The following table gives the performances of this assembly.

PERIOD	Operating time (hours)	PRODUCTION (kWh)	Power consumption (kWh)	Observations
02.04.1958 08.04.1959	171	16 730	500	Checking Braking problems
28.05.1959 18.11.1959	931	53 430	22 980	Problems with clutch and lubrication Destruction of bearing
13.04.1960 04.07.1961	3 980	62 970	121 260	Problems with lubrication, braking and heating of bearings; play in coupling
06.09.1961 12.04.1962	346	87 410	2 540	Stoppage to change airscrews
Total (kWh)	-	220 540	146 780	
(hours)	5 428	1 780	3 648	

It should be added that:

-- the assembly was connected to the network 372 times;

-- the length of the longest period of uninterrupted connection was 637 hours;

-- the maximum efficiency of the airscrew alone was 0.85, while that of the wind generator was 0.7.

To summarize, it may be concluded that:

-- the output curve exceeds predicted values;

-- the system for adjustment to wind speed operates correctly;

-- the automatic orientation system operates at a wind speed of 3 m/sec or more if the airscrew is turning;

-- the connection to the network is stable and easy to obtain;

-- the vibration of the blades is very slight;

-- there are no signs of damage due to wear and tear after 5428 hours of operation and 38,000 hours of exposure to the elements, aside from damage to the paint on the outside of the blades;

-- the admission of ambient air into the alternating generator should be avoided; /23

-- the excitation current would be better supplied by means of a rectifier;

-- the mechanical and electrical brakes were found to be adequate;

-- some lubrication problems remain to be solved if the assembly is to operate without monitoring.

Although the failures of this assembly -- which were all mechanical in origin -- show up very clearly in any review of its history, one should not minimize the excellent behavior of this wind generator with regard to the wind, that is, the stability of its coupling during movement and its satisfactory aerodynamic efficiency.

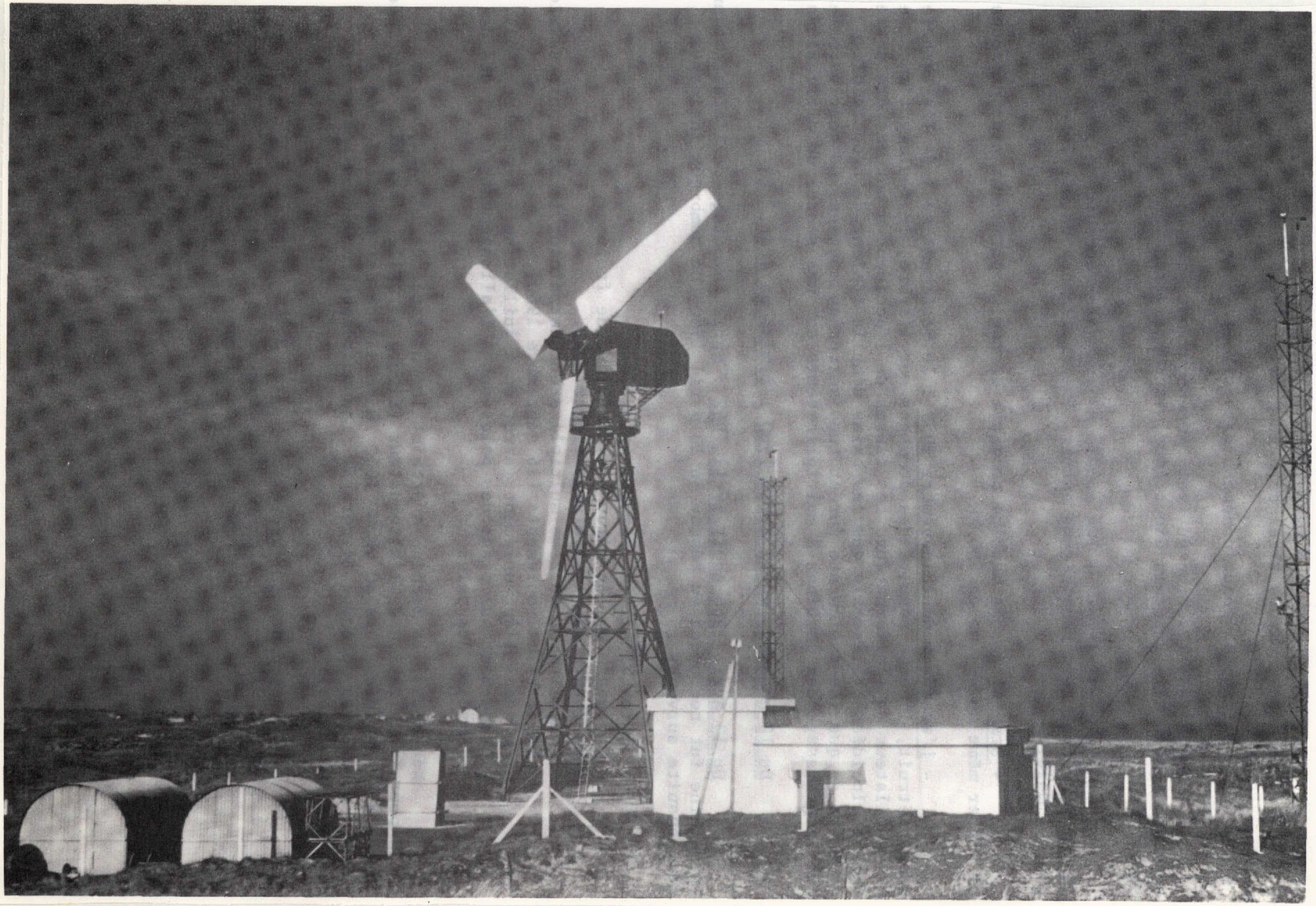

Fig. 7. The NEYRPIC wind generator at Saint-Remy-des-Landes (English Channel). 21.2 m; 132 kW.

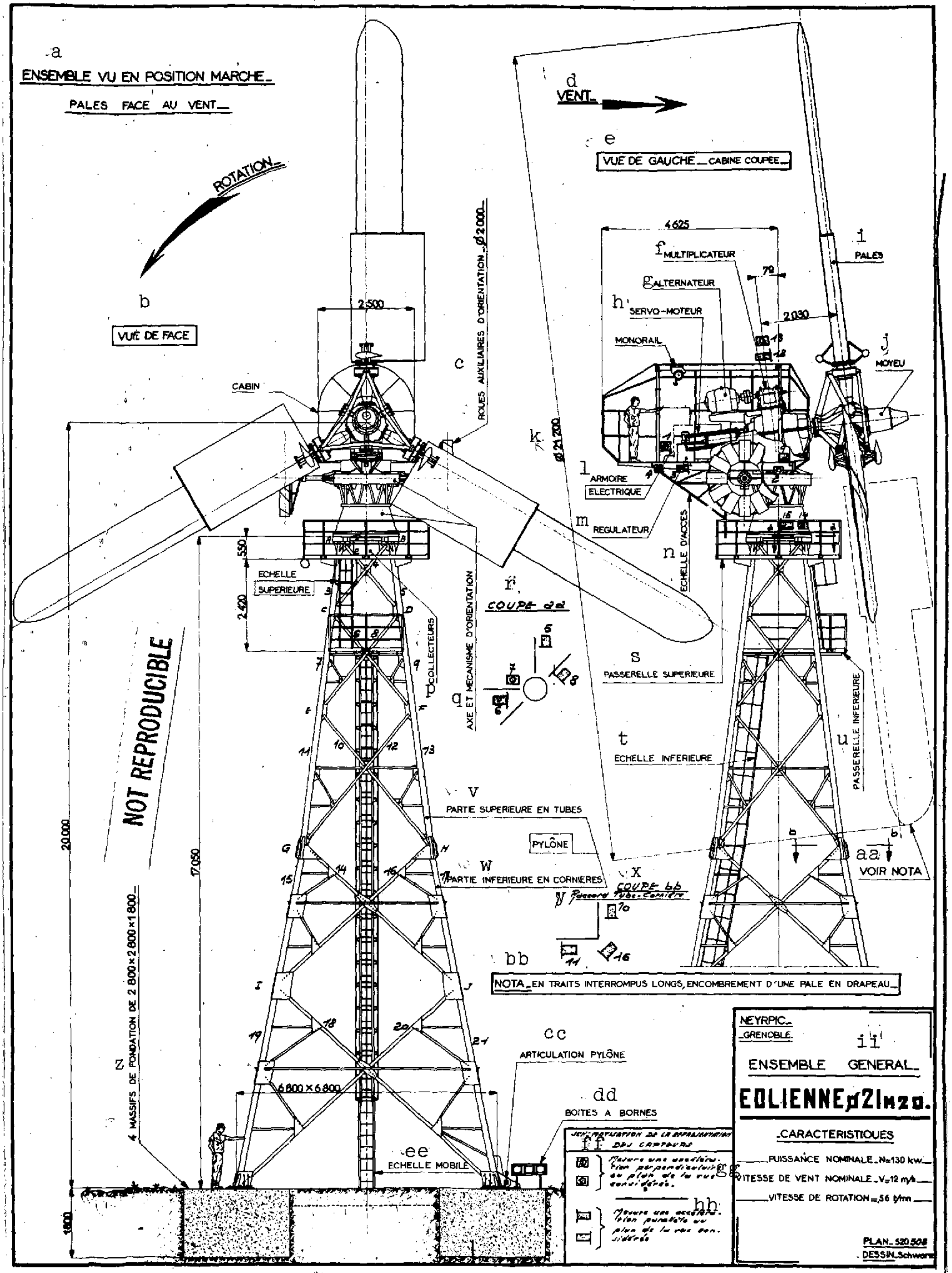

Fig. 8. [Caption and key on following page]

Fig. 8. Diagram of the first version of the pylon and blades of the 132 kW wind power generator.

Key: a. Overall view in operating position; blades face-on to wind
b. Front view
c. See auxiliary wheels for orientation; diameter 2000
d. Wind
e. View of left side; cross section of cabin
f. Step-up gear
g. Alternating generator
h. Servo motor
i. Blades
j. Hub
k. Diameter 21,200
l. Rack cabinet
m. Regulator
n. Access ladder
o. Upper ladder
p. Commutators
q. Shaft and orientation mechanism
r. aa cross section
s. Upper platform
t. Lower ladder
u. Lower platform
v. Upper part, constructed of tubes
w. Lower part, constructed of angle-irons
x. Cross section bb
y. Tube-angle-iron connection
z. Four foundation blocks, 2800 x 2800 x 1800
aa. See note below
bb. Note: long unbroken lines show the dimensions of a blade turned parallel to the direction of movement.
cc. Pylon articulation
dd. Terminal boxes
ee. Movable ladder
ff. Breakdown of representation of pickups
gg. Measurement of acceleration perpendicular to the plane of the wheel involved
hh. Measurement of acceleration parallel to the plane of the wheel involved
ii. General assembly: wind power generator. Characteristics: rated output N = 130 kW. Rated wind speed V = 12 m/sec. Rotation speed = 5.6 rpm. Blueprint 520508. Drawing: Schwarz.

2.1.1.4. The Nogent-le-Roi Fast Airscrew

On April 12, 1962, the airscrew was disassembled to be replaced with a faster airscrew.

It was decided to build another airscrew in order to eliminate one of the step-up gears. The new airscrew mounted on the Nogent-le-Roi assembly differed from the preceding in that it was constructed completely of light alloy (wrought AG 4), its rotation speed was 71 rpm rather than 47.3 rpm, and each blade was inserted in the hub by a trunnion. It was possible to adjust the setting with the blades at rest.

This airscrew operated for 307 hours, until September 5, 1963, when one of the blades broke. This incident concluded the tests at Nogent-le-Roi.

The failure of this airscrew was due to the fact that the 50% increase in rotation speed resulted in vibration of the necessarily flexible light alloy blades.

Wind tunnel tests performed in Chalais-Meudon on this fast airscrew with successive diameters of 2.5 and 4.5 m during the same period revealed the same destructive vibrations.

In 1965 plans were made for reassembling the first airscrew after transporting the wind power generator to a windier site in the Corbières.

2.1.1.5. Tentative Follow-Up Program to the Nogent-le-Roi Experiment

Following the tests on an experimental assembly, the EDF program provided for the construction and testing of a prototype assembly at Landunvez (close to Porspoder in Northern Finistère), and the subsequent construction and on-site assembly of a series of machines.

As a result, plans were made to continue the tests in 1959 with two 45 m airscrews placed side-by-side atop a hollow concrete pylon (similar to the refrigeration towers of thermal power plants), driving two 2 MW alternating generators (Fig. 6) rotating in reverse direction (since the wind tunnel tests had shown that the energy collected by a double assembly is 2.2 times that of a single assembly, the airscrew-pylon interaction becoming favorable). At one time there were even plans to construct a prototype with four 45 m airscrews, or 50 m airscrews as a variant, in order to obtain a unit power of 4 x 2.5 = 10 MW[4]. /25

Now, if the airscrews of the prototype and mass-produced generators are to be identical, it might be to advantage first to construct an experimental generator with a smaller diameter. Thus the EDF-Brest Romani project, finally researched in detail in 1963 [30], included only two 32 m airscrews. To obviate the use of step-up gears, whose operating history had revealed some drawbacks, 1000 kW alternating generators rotating at 66.67 rpm were to be used if the airscrews were two-blade models. In this case the peripheral speed of the blades would have reached 112 m/sec, that is, one-third of the speed of sound. However, the finished version would more probably have been equipped with three-blade airscrews, which are slightly faster, retaining a step-up stage on the order of 8, which would have allowed for the addition of a free wheel at the alternating generator input to preclude operation as a fan in low winds.

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[4] One might consider whether the use of airscrews with a slightly larger diameter (56 m, for example) for the same total output would not reduce the inconstancy of operation. Another aspect of the problem of choice of dimensions for the machine is that the optimum sizes for the various components of a wind power generator are not the same. The substructure, the support and the electrical system are inexpensive when the output is as high as possible. On the other hand, large airscrews are extremely costly, first, because their weight and cost increase as the cube of their diameter, while the output increases as the square of the diameter, and second, because the rotation speed decreases proportional to the diameter, with the result that the transmission and the generator become increasingly costly.

These projects, including the idea of resuming tests on the 800 kW version, were ultimately set aside due to the decrease in the cost of gasoline.

2.1.2. The Saint-Remy-des-Landes 132 kW Wind Generator [314, 315, 316, 317]

The characteristics of this machine (Figs. 7 and 8), which first underwent wind tunnel testing in Toulouse and was then installed at Saint-Remy-des-Landes in 1958, were as follows:

-- blade diameter 21.2 m;

-- rotation speed 56 rpm;

-- speed of asynchronous generator 1530 rpm;

-- rated output 132 kW in a 12.5 m/sec wind (45 km/hour);

-- Variable-step three-blade airscrew initially made up of welded aluminum, followed by a metal structure with plastic coating;

-- double-train step-up gear;

-- mounting on the ground, with the addition of a tilting system (subsequently eliminated).

Tests on the output yielded the following results:

-- rated output: 132 kW in a 12.5 m/sec wind;

-- maximum output: 130 kW in a 13.5 m/sec wind (Fig. 9);

-- maximum efficiency: 0.5 to 0.6 in a 10 to 13.5 m/sec wind.

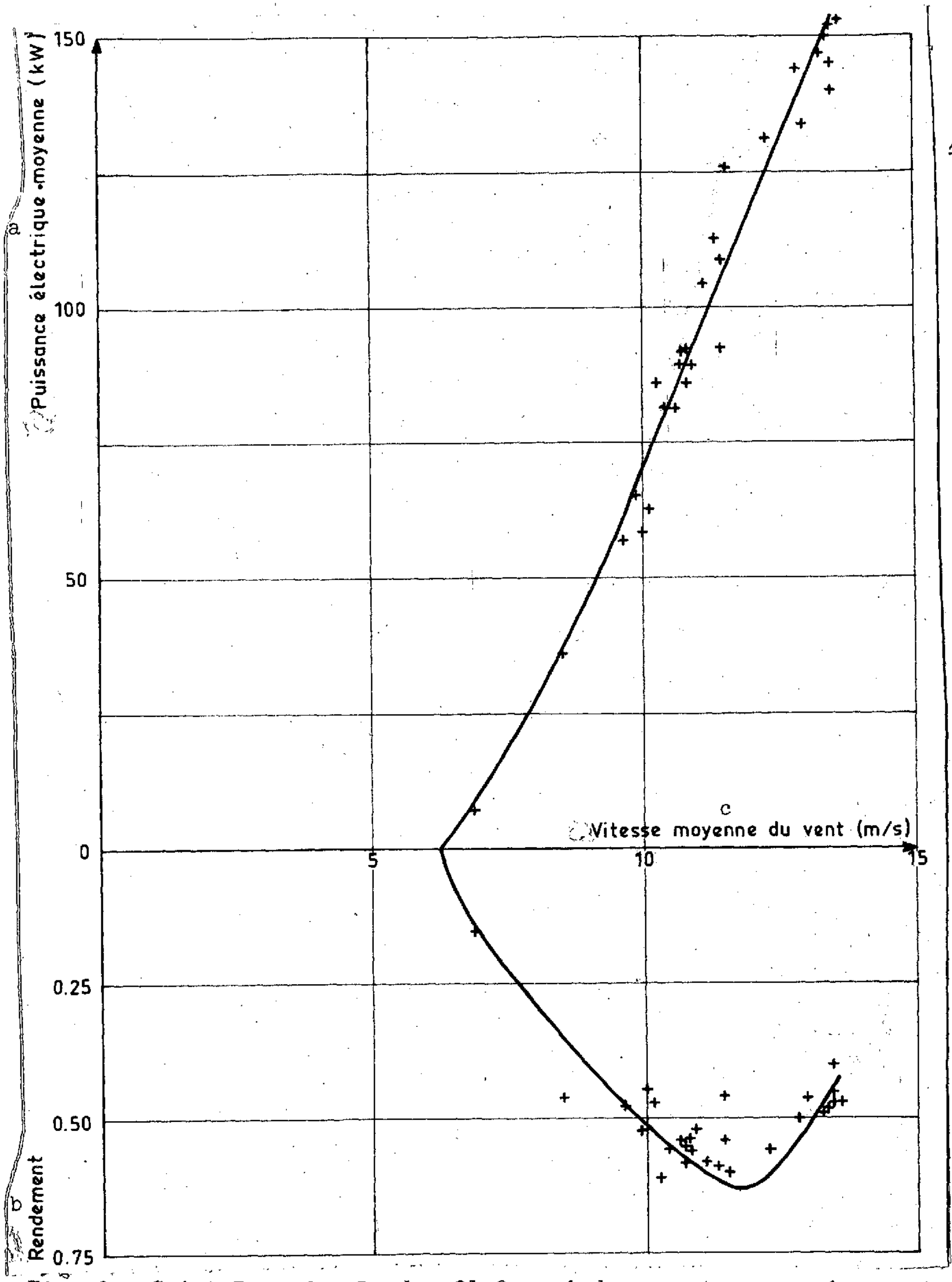

Fig. 9. Saint-Remy-des-Landes 21.2 m wind generator: maximum output over 1 hour and efficiency in comparison to Betz limit.

Key: a. Average electrical output (kW); b. efficiency; c. average wind speed (m/sec)

Tests begun in early 1959 dealt with: /27

-- development of a servo regulator (specifically resulting in elimination of the buffer battery in the hydraulic circuit of the servo motor);

-- determination of optimum setting;

-- measurement of stresses and vibrations of the pylon (3, 2 Hz) and blades (3, 5 Hz);

-- tests with generator free to swivel (satisfactory operation in absence of positioning system).

These tests were interrupted, first, by the necessity for considerable reinforcement of the support pylon, and second, by breakage of one blade on June 28, 1959. After a new set of blades had been mounted, taking into account developments made in 1964, the airscrew operated from November 1962 to March 1966, generating 700,000 kWh, a relatively low figure since the site was less windy than had been expected. The maximum production per month was 52,000 kWh. There was a total of 59 days of stoppage due to failure over these three years. In conclusion, the generator operated satisfactorily. Its mean efficiency over these three years was quite good: 0.34, in relation to the Betz limit, of course.

2.1.3. The Saint-Remy-des-Landes 1000 kW Wind Generator [311, 312, 317, 318] (Fig. 10)

Due to the satisfactory results obtained with the 21 m generator, the designer, NEYRPIC, proposed a new machine based on the same operating principles, also initially tested in the Toulouse wind tunnel; its characteristics were as follows:

Fig. 10. The Saint-Remy-des-Landes NEYRPIC wind generators (English Channel). Foreground: the 35 m, 1000 kW generator.

-- three-blade plastic swiveling airscrew placed downstream from the pylon;

-- adjustment by variation of blade setting on the basis of power regulation, that is, fixed setting up to 650 kW, variable setting thereafter, start-up dependent on wind speed (for 8 m/sec) and automatic connection to the network;

-- weather vane-type self-swiveling;

-- asynchronous generator, 1015 rpm, 3000 V;

-- metal lattice pylon 30 m high;

-- mounting on the ground and tilting of the mounted machine;[5]

-- two-stage step-up gear;

-- rated output 1000 kW in a 17 m/sec wind at the height of the airscrew (61 km/hour);

-- stoppage by turning blades sideways when the wind is less than 6 m/sec;

-- total weight (excepting substructure): 96 tons.

The wind generator was connected to the electrical network for the first time on June 13, 1963, four months after the beginning of the assembly process. It operated at an industrial level from June 30 to July 18, 1963, on which date there was an electrical failure in the system connecting it with the network.

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[5] Only the pilon was mounted on the ground and then tilted; a crane had to be used to set the machine itself in place.

Tests were resumed from October 1963 to June 1964. These /29
yielded the following results (Fig. 11):

-- satisfactory resistance to overspeed after disconnection from network;

-- vibration at a critical speed of 1300 rpm;

-- satisfactory output: 800 kW for 15 m/sec; the maximum reached was 1085 kW;

-- maximum efficiency 0.7 with a 13 to 15 m/sec wind;

-- average efficiency during period of operation: 0.47;

-- production: 500,000 kWh in 7 months; 222,000 kWh in November 1963 alone.

The roller bearings of the step-up gear from which the air-screw was suspended broke in June 1964. This breakage after 2000 hours of operation rather than the 200,000 hours predicted by computation was explained by poor design of the bearings. There were initial plans to repair the assembly, but these were subsequently abandoned and the wind generator was disassembled in June 1966.

2.1.4. Tests in Saint-Servan

Beginning in 1959, joint tests were performed by BEST-Romani and MEYRPIC-SOGREAH under the direction of the EDF on a reinforced plastic spar component 4 m long, subjected to considerable alternating stress and strain in the open air. These tests made it possible to control the very slight and gradual development of

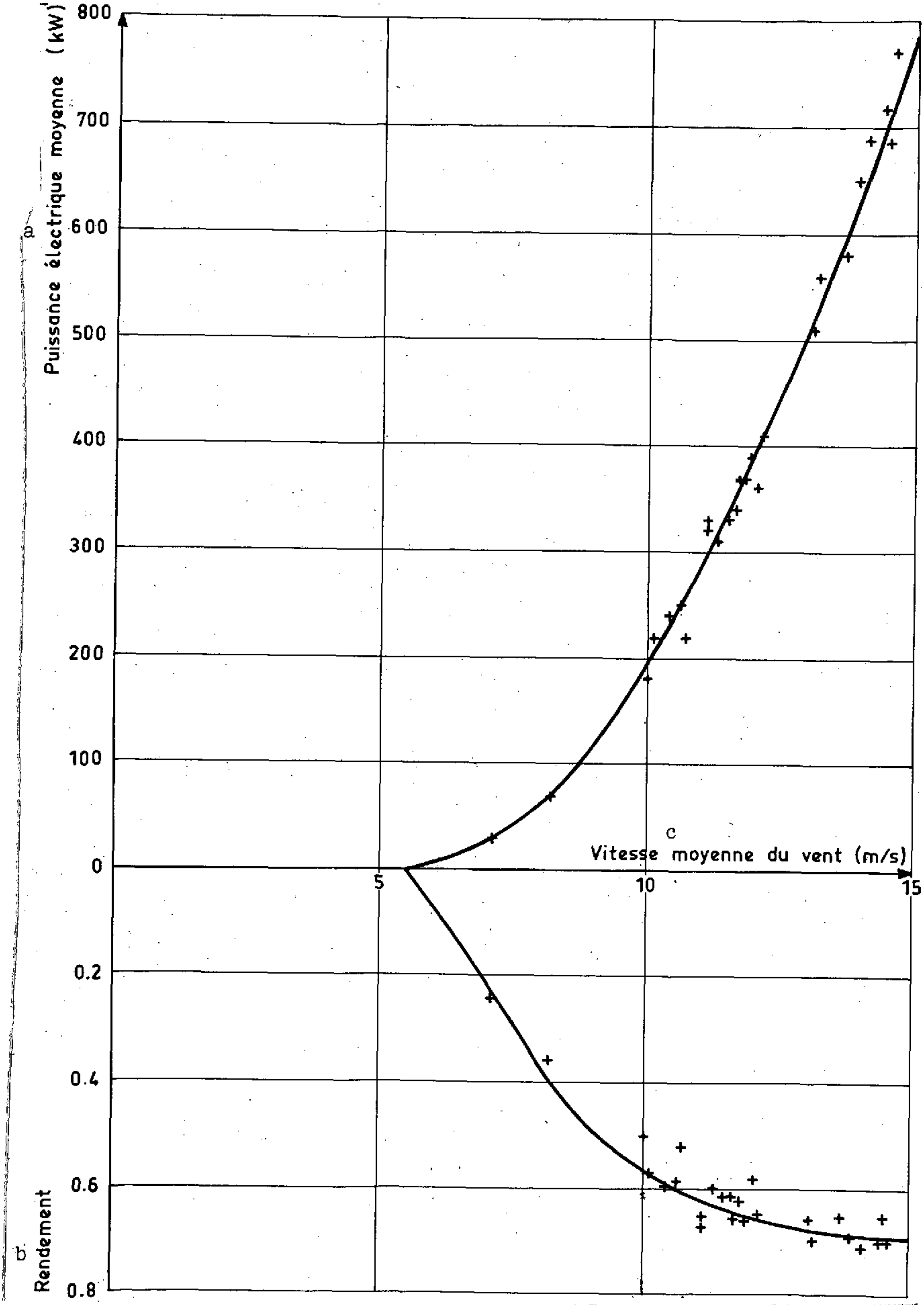

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Fig. 11. [Caption and key on following page]

Fig. 11. Saint-Remy-des-Landes 35 m wind generator: average output over 1 hour and efficiency in relation to Betz limit.

Key: a. Average electrical output (kW)
b. Efficiency
c. Average wind speed (m/sec)

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the properties of this material over time for the manufacture of wind airscrews (more than 100 million test variations were made).

2.1.5. The J.B. Morel Wind Generators [313] (Fig. 12)

The French Electrical Authority has also been interested in horizontal-axis wind-driven wheels and vertical-axis wind generators, particularly those patented by J.B. Morel. Initially this inventor had tested a wind-driven "motor dam" with horizontal axis perpendicular to the direction of the wind.

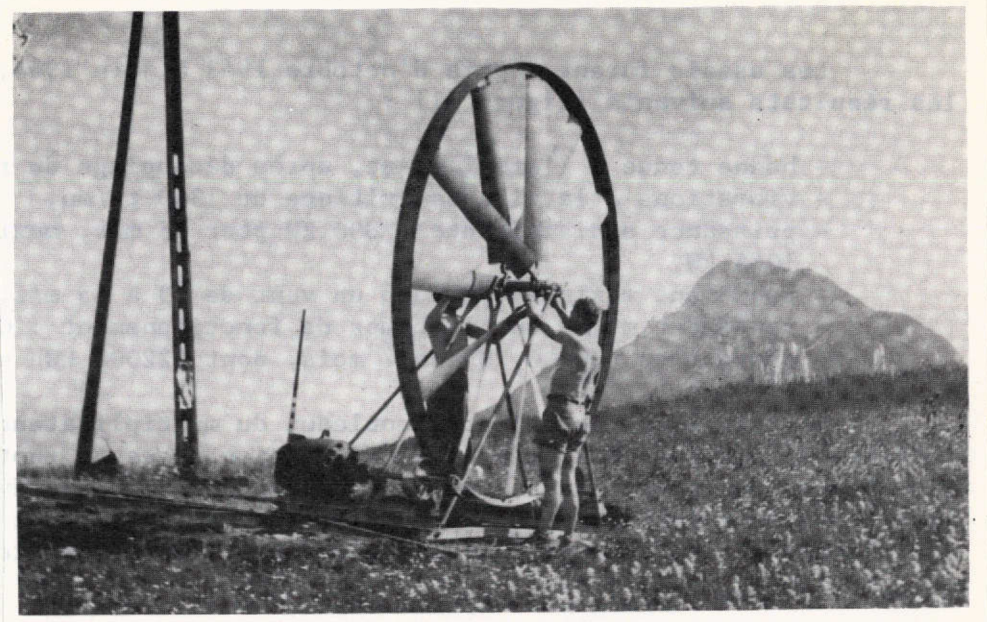
2.1.5.1. Airscrew with Blades Secured between a Circular Rim and a Reduced Hub

A prototype 3 m in diameter with a wheel with rim equipped with blades has undergone wind tunnel testing in Domene (Isère) and subsequently on the Saint-Nizier plateau at an altitude of 1100 m in 1951. The advantages of this device are:

-- elimination of the drive shaft, the energy being transmitted by the rim;

-- elimination of the step-up gears, mechanical energy being available at high speeds;

-- the possibility of using thin-profile blades with high aerodynamic efficiency, their stiffness being ensured by their tension between the rim and the hub of the wheel;



The J.B. Morel wheel on the Saint-Nizier plateau.

—The Mondragon wind generator after the accident.

Fig. 12.

-- the stabilizing effect of the rim.

These tests showed the efficiency of the machine to be as high as 0.45 and the output 4.8 kW with a 15 m/sec wind. No follow-up studies have been performed.

Another inventor, M. Doffin, tested a model of the same type of airscrew in one of the Poitiers wind tunnels in 1966, but without financial backing from the EDF. /31

2.1.5.2. The Vertical-Axis Wind Generator

This generator was designed to combine the simplicity of the old windmill with the high efficiency of contemporary contoured-blade airscrews. This type of wind generator has the advantage of not requiring positioning in the wind, but it must be started; however, this is not a serious drawback for a device connected with a network.

Wind tunnel tests in Saint-Cyr with a three-blade machine with a span of 1.75 m yielded an efficiency of 0.23 (output 300 W with a 10 m/sec wind).

As a result of these tests, an experimental 7 kW machine with characteristics as given in the following table was built and tested in the Fressinades at Mondragon, along the Donzere-Mondragon canal. It was in operation from August 9 to October 8, 1954, when it was destroyed by a mistral squall following a failure in the braking system. These tests also yielded an average efficiency on the order of 0.23.

It was necessary to resume these tests in Mondragon with a smaller 5 kW machine forming a cone with a larger angle at its apex so as to obtain a less "peaky" efficiency curve, that is, a

CHARACTERISTICS OF J.B. MOREL VERTICAL-AXIS WIND GENERATORS

Rated output (kW)	7	5	90	500	1200
	(completed)		(planned)	(planned)	(planned)
Diameter of wheel (m) High	4.2	2.0	3.9	12	18
Diameter of wheel (m) Low	8.5	8.5	20	40	60
Elevation of wheel (m)	5.7	5.7	14	36	54
Rated rotation speed (rpm)		50	50	14.3	14.3
Wind speed (m/sec)	10	10	15	15	15
Cost without alternating generator (in thousands of francs)				50 (1953)	110 (1955)

maximum efficiency plateau which would be valid for a broad range of wind speeds. Tests were begun, but were interrupted by the J.B. Morel company in 1955 due to financial difficulties.

Nevertheless, preliminary designs for 90, 500 and 1200 kW wind generators have been laid out with the aid of the EDF, allowing for an average efficiency on the order of 0.25. The few tests performed have primarily shown there to be a great many problems which must be overcome with this type of machine. Consequently the cost price of this type of generator, which is already quite high, is prohibitive in comparison to that of generators with a horizontal-axis airscrew.

2.2. Other Large Models

2.2.1. The Andreau-Enfield Wind Generator (1950 to 1957) [202]

The 100 kW wind generator tested at Grand-Vent (Fig. 13) by the Gas and Electricity Company of Algeria (EGA) is a very specific type of generator and its history is therefore of some interest.

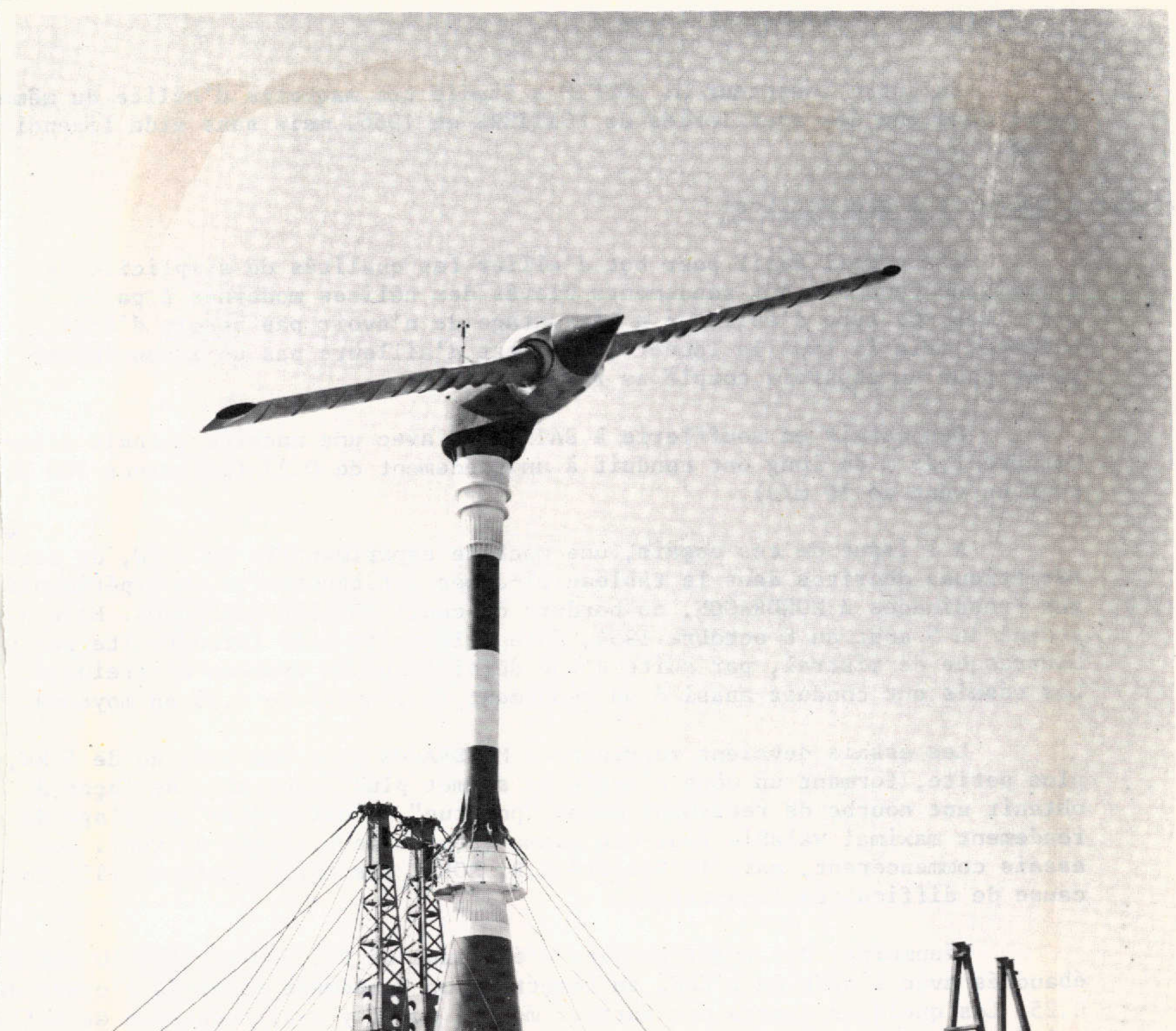


Fig. 13. The Andreau-Enfield wind generator in Grand-Vent (Algeria). 24.4 m; 100 kW.

This was the Andreau-Enfield machine designed in 1950 by Enfield Cables Ltd., for the British Electricity Authority. The blades, designed by De Havilland Propellers, Ltd., are hollow; as they rotate, centrifugal force expels air from their ends, resulting in suction at the center. This negative pressure is used to drive a turbine located in the barrel of the wind generator (Andreau patent No. 617331 of October 8, 1951).

The detailed characteristics of the assembly were as follows:

-- airscrew diameter 24.4 m;

-- rotation 100 rpm under a 13.5 m/sec wind (48 km/hour);

-- suction flow rate 1655 m^3/min;

-- inclination of blades automatically adjusted with wind speeds of more than 48 km/hour so as to maintain a constant airflow rate in the turbine;

-- rated output 100 kW for a wind speed range of 13.5 to 29 m/sec (48 to 105 km/hour);

-- blades swiveled sideways with a wind speed of more than 105 km/hour;

-- 100 kW, 415 V synchronous motor;

-- height of tower 30 m above ground.

Initially the machine was to have been installed at the top of the hill Mynydd Anelog, Alerdaron (Caernarvonshire, Wales), but it was first installed in Prae-Wood, St.-Albans (Hertfordshire) in 1953 for testing purposes. Unfortunately, this was a wooded site, and thus an area where the vertical wind distribution was highly disturbed. As a result, there were vibrations of the airscrew and the project was abandoned by the English researchers.

In 1957, EGA recovered the machine to reassemble it at Grand-Vent (Fig. 14) on a better site than the St.-Albans site. The wind generator operated at Grand-Vent for 180 hours, with an output varying from 80 to 130 kW.

The EGA tests, under the direction of Mr. Delafond, revealed the weak points of the system, specifically, flaws in the design of the blade orientation mechanisms and stops, and leaks in the rotary joints of the negative pressure column. These minor problems have been solved but the installation was still abandoned due to safety reasons.

The conclusions from operation of this generator are as follows:

-- the choice of site is of basic importance; the area must be one in which the spatial distribution of the wind is as uniform as possible;

-- the efficiency of the Andreau system is quite low (20%) /35
due to the kinetic energy losses of the air expelled at the end of the blade (lack of a scroll for recovery), entry of air at the joints, considerable losses of head in the negative pressure circuit, and especially due to the fact that the efficiencies of each of the four machines connected in series (wind generator, centrifugal blower, negative pressure turbine and alternating generator) must be multiplied by each other; this was a fact which had already been determined in previous tests on a large model performed by the EDF and Andreau at Saint-Cyr-l'Ecole;

-- articulated blades should not be used.

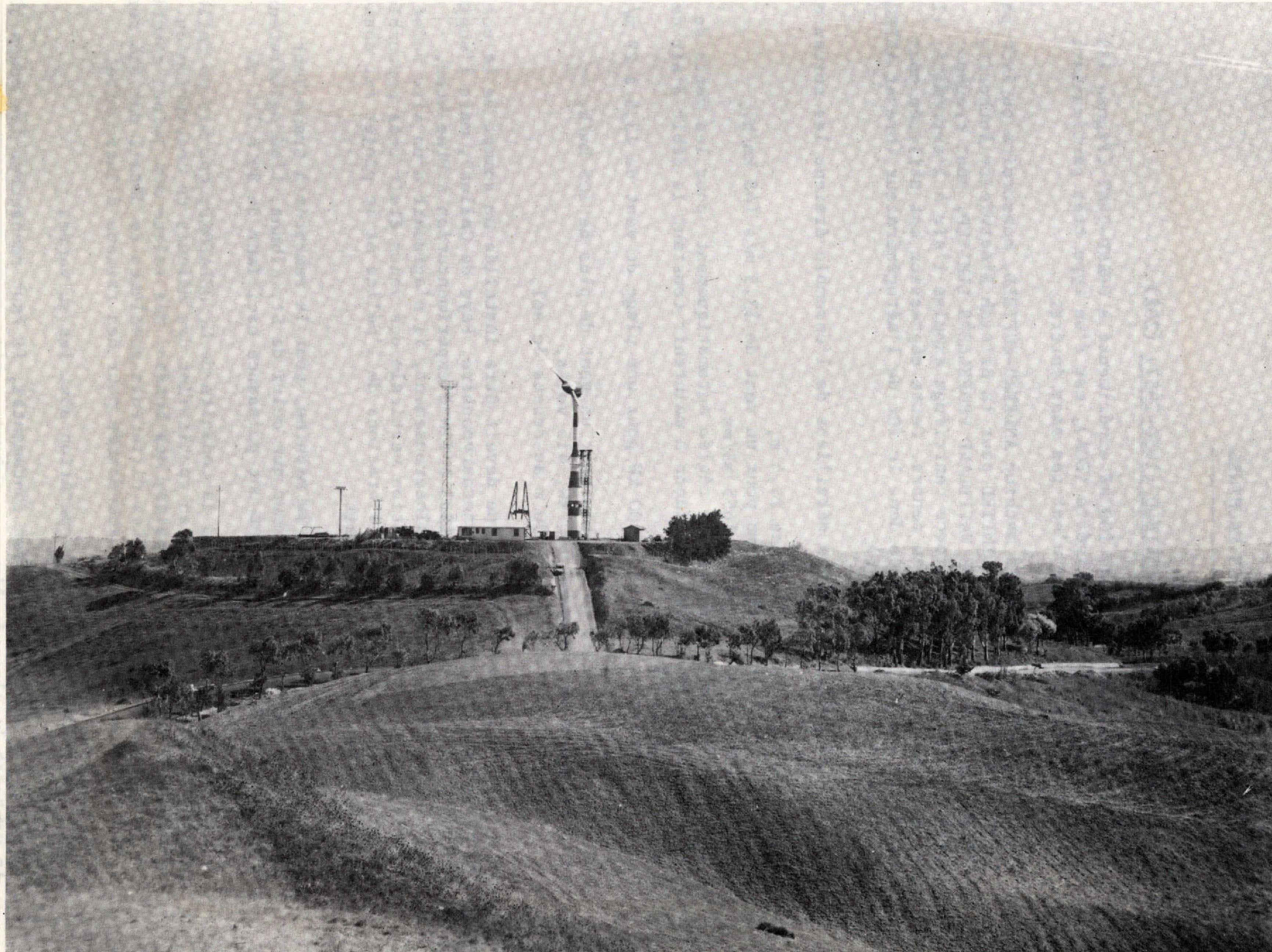


Fig. 14. General view of the Grand-Vent site in Algeria.

[Fig. 14 continued on following page]

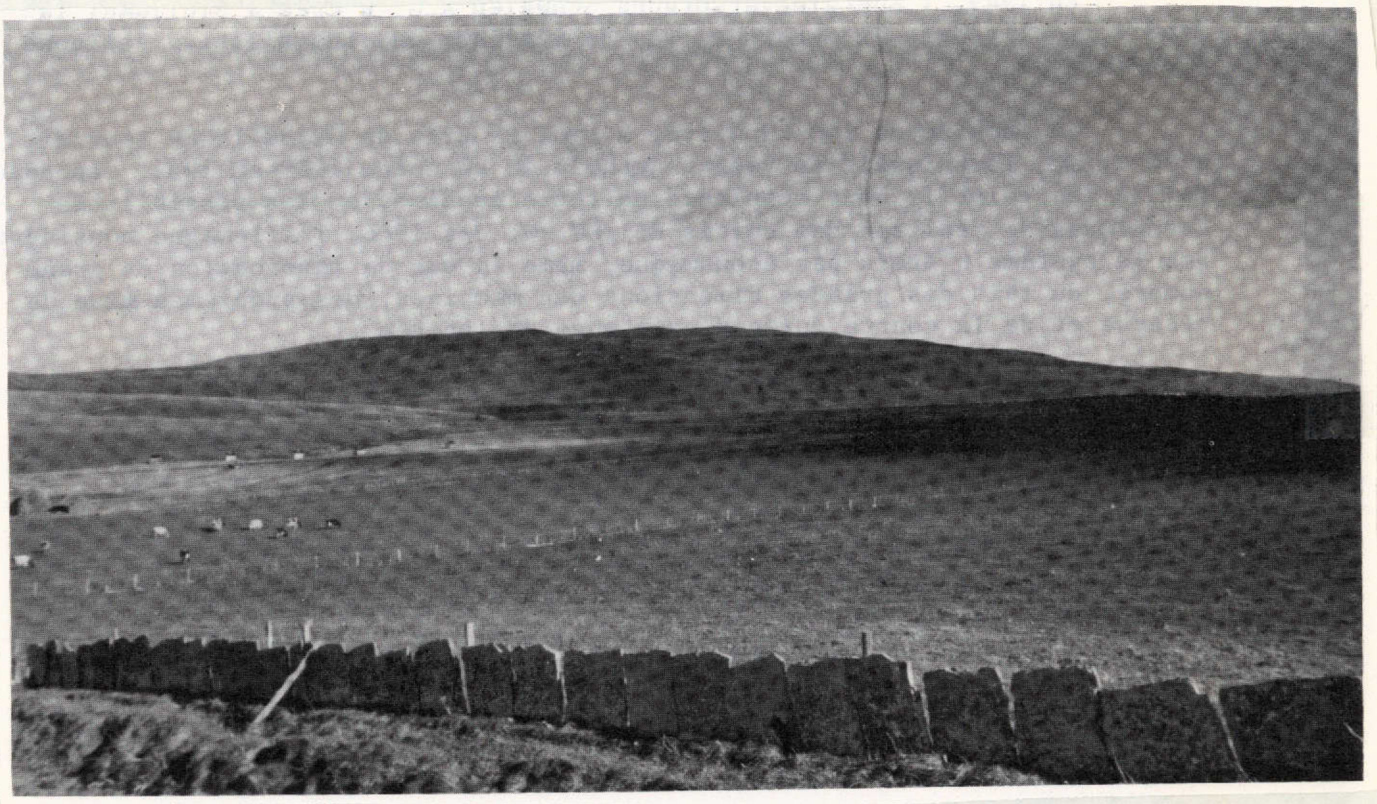


Fig. 14a. Costa-Head in the Orkney Islands. Site chosen for installation of a 100 kW wind generator (one of the windiest areas in the world).

The efficiency of the blades alone was fairly good (0.73), although they were necessarily poorly contoured. This shows that it is not necessary to give detailed attention to the aerodynamic characteristics of the central part of the airscrew, and the design of the airscrew may be simplified.

2.2.2. The Orkney Islands Wind Generator [107, 111, 203]

In 1950, the North Scotland Hydroelectric Board (NSHEB) asked the John Brown Company to design an experimental 100 kW wind generator to be installed on the hill of Costa-Head in the northern part of the main island in the Orkney chain. The generator was in operation for a very short period of time in 1955, connected to the public electrical system in parallel with diesel-powered electrical generating units. The designer hoped to obtain information which could be used to develop a 250 kW machine with a diameter of 23.8 m, but these plans were apparently not carried out.

The detailed characteristics of the assembly installed in the Orkney Islands were as follows:

-- rated output 100 kW with a 15.5 m/sec wind (56.3 km/hour);

-- slowdown under a wind speed of more than 26.5 m/sec (95 km/hour);

-- height of pylon 24 m above the ground.

However, the excessive number of articulations and possible orientation movements of the blades were disastrous to this project.

2.2.3. Danish Wind Generators [108, 204] /36

Denmark has been interested in wind power for a long time. Since formerly the Danish public power network was not interconnected, a number of towns had individual wind generators. In 1939, the Lykkegaard Company was manufacturing wind generators 18 m in diameter able to operate under wind speeds of 4 to 11 m/ /sec and generating 50 MWh/year (cost 1100 crowns). In 1941, 64 machines were generating 1.8 GWh/year, and from 1940 to 1947 the energy produced by wind generators was 18 GWh. One Lykkegaard machine purchased by the EDF was in operation in Clamart for a few months in 1948; its design was found to be somewhat outdated.

Wind tunnel testing of wind generators was resumed after the war, followed by tests on an 85 kW machine with a cost of 612 crowns per kW. Three other wind generators with outputs ranging from

30 to 75 kW were built in 1942. These cost approximately 900 crowns per kilowatt and the cost price of the power generated was 0.3 F/kWh in 1948.

Subsequently, the Sydolstjallands Elektricitets Aktieslskab (SEAS or Southeastern Zeeland Electrical Authority) successfully tested 13 kW wind generators in Vester-Egesborg (1949) and 45 kW generators on Bogo Island (1952). In 1954, at the instigation of J. Juul, the SEAS decided to construct a 200 kW machine in Gedser, inaugurated in 1957 and put into operation in 1959. There were subsequent problems in operation in the form of vibrations and pumping of aerodynamic origin due to interference between the wakes of the blades.

It appears that the combination of the dissolving of the J. Juul Co. in 1965, mechanical failures and a drop in the price of gasoline resulted in the abandonment of wind power in this country, where it had been extremely important.

2.2.4. Wind Power in Germany [119, 209]

In 1949, the Schwalen Power Supply System set up a Wind Power Study Society in Stuttgart for the purpose of constructing and experimental wind power station.

The 100 kW machine erected in Stotten close to Geisslingen operated at 34 rpm and supplied up to 90 kW to the public power network between 1959 and 1961. However, despite the relatively good results obtained with this generator and the technical possibilities of constructing 100 kW units, in 1966 Germany decided that the system was not economical even if a large number were to be manufactured, due to the large size of the machines, problems of power storage and the short life of the units.

2.3. Small Wind Generators [200, 210, 211] /37

Although large wind generators generally yielded disappointing results, low-power machines, on the other hand, have usually proved satisfactory. These are wind generators of less than 10 kW, used for pumping, for electrical power supply in isolated areas (lighthouses, islands, explorer camps, etc.) in connection with a series of batteries or an electricity generating unit.

In France, after the EDF tests were discontinued, the Brest-Romani Company, which had built the Nogent-le-Roi wind generator, was dissolved in 1966. The Aerowatt Company, which replaced it, took out a patent prepared by Mr. Seger dealing with regulation of the rotation speed by various methods, including aerodynamic stall. This involved situating the operating range of the machine in the descending part of the characteristic power-wind speed curve; as a result, the motor torque decreases in high winds. The airscrews, which are simpler, are not twisted. They are adapted to operation in low-speed winds (5 to 7 m/sec) and start at 3 m/sec.

Since 1970, Aerowatt has built approximately 200 power generators ranging from 24 W to 4 kW. These are used particularly by the Lighthouse and Beacon Service as a safe power supply for various lighthouses (Fig. 15) [211]. The cost price of installations with series of lead batteries is on the order of 10,000 F/ /kW in 1974 for outputs of less than about 10 kW. Under these conditions, a 15 kW (18 m) machine costing 150,000 F will amortize in 10 years at a rate of i = 10%, and, generating 70,000 kWh/ /year, will have a cost price of:

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Fig. 15. The Faraman lighthouse (mouth of the Rhône) powered by and Aerowatt 1100 W wind generator.

3. Economic Considerations and Prospects for the Future

Publications on wind generators are frequently crowded with economic considerations for which the bases of computation, for the most part, unfortunately cannot be controlled. We will mention only those which seem to be most serious. All the costs are given in current francs for the year and in constant francs for the beginning of 1974 [206].

In 1957, Dowsett Holding, Ltd. of London proposed the following installations to be based on a 25 kW generator:

Site	Power storage system	Cost £ (1954)	Cost F (1974)	PRODUCTION (kWh/an)	Cost per kWh F (1974)
Australia	interconnection	6 000	180 000	43 500	0,38
India	pumping (10 kW)	7 000	210 000	300000 m3/year	-
St-Hélène	battery (225 A-h)	9 000	270 000	85 000	0.32
-	diesel-electrical (7 kW)	7 000	210 000	85 000	0,80

Fairly extensive economic studies were performed in Great Britain in the early 1950's, particularly by E.W. Golding. These may be summarized by the following table:

Output (kW)	Cost per installed kW £ (1955)	Cost per installed kW F (1974)	Cost per kWh in F (1974)
1 - 4	200	6 000	0,1 to 0,7
10 - 100	150	4 500	0,1 to 0,4
1 000 - 10 000	50	1 500	0,34

These costs are comparable to those of French and Danish wind generators which have been planned or constructed.

SAINT-REMY-DES-LANDES	:	130 kW	- 24,000,000 OF(1955)	or 4 500 F/kW	(1974)
- - - -	:	1 000 kW	- 2,400,000 F(1961)	or 4 300 F/kW	(1974)
NOGENT-LE-ROI	:	800 kW	-170,000,000 OF(1954)	or 5 200 F/kW	(1974)[6]
EDF (BEST-Romani project)	:	2 000 kW	- 3,300,000 F(1963)	or 2 700 F/kW	(1974)
DENMARK	:	75 kW	- 9,000,000 OF(1948)	or 3 800 F/kW	(1974)
-		200 kW	- 20,000,000 OF(1954)	or 2 500 F/kW	(1974)

To summarize, the investment costs for an experimental generator would be on the order of 3000 to 4500 F/kW in 1974. This remains to be confirmed, since for industrial installations these figures may be cut by a factor of 2 or 3 in accordance with the results obtained in Denmark and England and the predictions of French constructors in 1963. /40

A brief glance at future plans in other countries: the report by G. Massart [122] describes developments in the US; the University of Montana is studying a new type of wind generator, and the University of Oklahoma is oriented towards large systems and offshore installations. The Lewis Research Center is studying 100 kW wind generators. The contracts involved are in excess of 1 million dollars for 1973 and 1974. Ocean Energy of Blairsville, Pennsylvania, is attempting to develop a small, simple wind generator of 5 to 8 kW with a Tergal airscrew for domestic heating in winter.

Finally, we might mention possible developments in regard to series of wind generators on aligned floating structures in the ocean, producing hydrogen which will be stored in submarine tanks and burned in thermal power plants on land [123]. After examining a large model of this type, W. Heronemus seems to assign the

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[6] Including substructure.

preference to assemblies with outputs on the order of 1 to 6 MW composed of standardized wind generators (10 m, 20 kW, 11 m/sec).

Conclusion /41

The initial efforts of the French Electrical Authority toward the development of wind power have dealt with exploration of the French national territory to measure the amount of wind power theoretically available (Fig. 1).

A second phase involved testing two types of wind generators:

-- an average-power 130 kW machine (Fig. 7) which was found highly satisfactory;

-- two high-power machines. The first (800 kW, Fig. 2) presented a number of small technical problems which were subsequently solved. Nevertheless this generator demonstrated the impossibility of operating machines with diameters on the order of 40 to 60 m without problems. The second high-power generator (1000 kW; Fig. 10) confirmed the production capabilities of these generators over its short period of operating time. The 800 kW machine was installed in a low-wind site close to Paris, and it was found to be a better technical prototype than the 1000 kW generator installed close to the coast of the English Channel.

The information provided by the experiments performed by the EDF and abroad may be summarized as follows:

-- Small wind generators (1 to 10 kW), which are fully developed technically, are of value at local sites when there is no interconnected electrical power network. Despite the high unit cost of these wind generators (5000 F/kW), there is unquestionably a market for them in undeveloped countries bordering on the ocean or in temperate zones, or for highly specialized uses such as in isolated lighthouses, water pumping for agricultural purposes, hot water storage, etc.

-- Large wind generators (1 to 10 MW) joined to an interconnected public power supply may be installed at windy and relatively uninhabited sites, and despite their irregular production, may be considered a means of supplementing the power output in certain power supply situations in countries with favorable sites, conditions which are not found in combination in developed countries.

-- Currently it seems to be to advantage to try to develop average-power generators with outputs on the order of 100 kW.

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